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The research described herein involves a new digital image compression algorithm. A hybrid low-pass filter/fractal technique was developed, taking advantage of the fact that fractals afford a remarkable way of compressing high frequency data. The low frequency content of the image is stored without loss, and then fractal image processing is used to "touch-up" the high frequency features, with some loss. An image compression software system has been built around this. The system handles 24-bit digital images of arbitrary resolution. Compression is quick - for example, the system compresses a still 1280 x 1024 (high-definition) image in a few seconds on a Personal Iris (6 MFlops); and also decompresses in a few seconds. At low compression (around 15:1) the compression is visually lossless. At high compression (around 100:1) there is some loss, but not much.

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FINAL TECHNICAL REPORT

1. INTRODUCTION

This report summarizes in brief the research in fractals, wavelets and image compression, carried out by the Principal Investigator, M. A. Berger, over the past three years, under the auspices of the Air Force Office of Scientific Research under Grant. No. AFOSR-90-0288 entitled "Probabilistic Methods for Image Generation and Encoding." The technical details of the research were described in full in the First and Second Annual Reports submitted to AFOSR. During this third period of research the PI concent rated on efficient software implementations of his image compression algorithm, both at his laboratory in the Microelectronics Research Center at Georgia Tech, and at the Weizmann Institute in Israel where he has been a visitor since 1 January, 1993.

Over the past three years the PI has worked on several topics, including:

- Fast generation of continuous wavelets as attractors of iterated function systems
- Using iterated function systems to represent solutions of multi-dimensional dilation equations
- Color and grayscale digital image compression using a novel hybrid Fourier/fractal algorithm
- Efficient construction of bit strings for fast generation of attractors from iterated function systems

The underlying theme of the PI's work has been development of techniques using iterated function systems for applications in imaging (compression) and graphics (curve and surface generation, wavelets), and, most recently, the efficient implementation of these techniques in software on a UNIX/X-Windows platform.

Another milestone of the three years' work was the setting up of a digital video and graphics lab at Georgia Tech, linking together Silicon Graphics workstations, a laser video recorder, a Betacam video recorder, scanner, camcorder and other peripherals. The PI's lab is housed in Georgia Tech's Microelectronics Research Center, and the primary research carried out in the lab is image and video compression. During the tenure of the above-mentioned AFOSR grant the PI published several papers and a textbook ("Introduction to Probability and Stochastic Processes," by Springer-Verlag, 1992), founded a new journal ("Random and Computational Dynamics," by Marcel-Dekker, 1992), was appointed to the National Academy of Science Panel for the Assessment of NIST, was appointed to the Deutsche Forschungsgemeinschaft (DFG) Review Panel for the DFG-Forschergruppe "Dynamische Systeme" at Universitat Bremen in Germany, and ran the group projects for the Pittsburgh Supercomputing Center Summer Institute each summer.

2. WAVELETS

The PI discovered a link between wavelets and iterated function systems, whereby graphs of wavelets can be generated as projections of attractors of multi-dimensional iterated function systems, involving only two affine transformations. Construction of these systems is based on the dilation, or "scaling" equation satisfied by the "scaling functions" from which the wavelets are the quadratic mirror filter. In fact it is the scaling function which the iterated function system produces in its fundamental from.

The attractor of an iterated function system can be generated via the orbit of the dynamical system, on account of the Ergodic Theorem which ties temporal averages to spatial averages. The PI also addressed the issue of random vs. controlled dynamics, and was led to discover a construction for the most efficient bit string to generate the dynamics. The PI's algorithm for generating graphs of wavelets can be used to produce a fast continuous wavelet transform, but the PI has not yet implemented this fully in software.

His work on wavelets led the PI to a technique for generating graphs of solutions to general dilation equations, even in a multi-dimensional setting. For an n-dimensional dilation equation the required iterated function system involves 2^n affine transformations, operating in a high-dimensional space. (The specific dimension depends on the lattice support of the scaling coefficients.) Such dilation equations are used for surface generation via sub-division methods. The PI also carried out rigorous analyses of the existence, uniqueness, integrability and smoothness of solutions to dilation equations, and convergence of iterated approximants, under general conditions on the scaling coefficients, in collaboration with Y. Wang (Georgia Tech). This work led to the study of infinite matrix products and bounded semi-groups of matrices, and led to the resolution of two conjectures of Daubechies and Lagarias.

The PI tried to extend this further to (genuine) continuous multi-dimensional wavelets, but was unable to come up with an appropriate definition of what these wavelets should satisfy. This is still open, to the best of the PI's knowledge.

3. IMAGE COMPRESSION

The PI spent the majority of his time these past three years developing and implementing his image compression algorithm, based on a novel hybrid Fourier/fractal technology. After researching fractals for many years, the PI realized that whereas fractals represent a powerful tool for compressing high frequency image information, they perform poorly with smooth image components. With this in mind, the PI developed a compression algorithm which uses Fourier-based projection methods for storing the low-frequency content of an image, and fractals for storing the high-frequency content. The key to the algorithm is a critical switching capability, which enables the fractal compression to enter exactly at the point where the low-frequency compression stops, thus avoiding the necessity to store two compressed files of the entire image -- one for the low-frequency component and one for the high-frequency component.

The PI also developed rigorous error estimates for the compression loss, based on how well the high-frequency components of the image on two different scales can be statistically correlated. These estimates enable one to set various compression parameters and to bound the loss a priori.

The PI invested a lot of time in implementing his compression algorithm in software, and in optimizing its performance. In its present state the algorithm can compress a high-resolution 1280 x 1024 24-bit color image on a Silicon Graphics Personal Iris workstation in under 60 seconds, and decompress and display the image in under 3 seconds. The algorithm is now fast enough to run on a PC 66 MHz computer and, with some motion compensation, can decompress a color video sequence of 320 x 240 resolution at a real-time rate of 24 frames per second using software alone. The compression algorithm is highly parallel and can be implemented in hardware so as also to achieve the same real-time video rate. Most of the modules of the compressor are available in standard chipsets, with the exception of one key module which performs a two scale multiple cross-correlation.

The PI's compression algorithm is not an ISO standard, like the JPEG and MPEG algorithms, and thus its primary application is for closed systems, which do not need to communicate with other applications. Its advantages over JPEG are

- Better quality at the same compression ratio
- Faster decompression
- Resolution independence, so that the same compressed file can be used to generate the image at varying scales
- No blockiness artifacts -- even at very high compression ratios the decompressed image is guaranteed to be continuous

4. EQUIPMENT & PERSONNEL

Video and Graphics Lab

The PI set up a computer laboratory at Georgia Tech, based on two Silicon Graphics Personal Iris workstations, a SONY laser video recorder, a SONY Betacam SP video recorder, a JVC S-VHS recorder, a Howtek Scanmaster III scanner, a Dunn analog film recorder, a frame grabber, a CCD camcorder, and other peripherals. The laser video recorder is driven by the workstations using special RS-232 software drivers, which enable live recording from the workstation onto the laser disk in component RGB form, with variable speed playback. From the laser recorder the images can be dubbed to the Betacam or the VHS recorder in composite form. Image capture can be performed using the Howtek scanner or the frame grabber. Image display can be on the workstation or a full-screen SONY Trinitron monitor at NTSC frequencies, and hardcopy can be made either through the film recorder (color prints or slides), or through an Apple Laser-Writer printer (grayscale). In addition the PI purchased administrative equipment, including two 486 PC's, a PaintJet color printer, three Apple Laser-Writer printers and various software packages for PC's.

Personnel

Personnel supported in full or in part on this grant include the Principal Investigator (M. A. Berger), a technician/programmer (J. Anderson), a graduate student (R. Coleman), a Ph.D. student (K. Leeds) and administrative assistants (J. Chambers and D. Little). In addition three consultants were hired as part of a visitor program (L. Arnold, T. Bedford, Y. Kifer).

5. PUBLICATIONS & OTHER RESEARCH GRANTS

Following are the publications written by the PI during the tenure of this grant.

Berger, M.A., Lectures on Products of Random Matrices, Lecture Notes, Georgia Institute of Technology, 1990.

Berger, M.A., Lectures on Wavelets, Lecture Notes, Georgia Institute of Technology, 1990.

Berger, M.A., Review of Fractals Everywhere, *Stochastics and Stochastic Reports,* 30 (1990), 193-204.

Berger, M.A., Wavelets as attractors of random dynamical systems, in *Stochastic Analysis: Liber Amicorum for Moshe Zakai,* E. Mayer-Wolf et al., eds., Academic Press, San Diego (1991), 75-90.

Berger, M.A., IFS algorithms for wavelet transforms, curves and surfaces, and image compression, in *Lecture Notes in Statistics, Vol. 74: Stochastic Models, Statistical Methods and Algorithms in Image Analysis,* P. Barone et al., eds., Springer-Verlag, New York (1992), 89-100.

Berger, M.A., Random affine iterated function systems: curve generation and wavelets, *SIAM Review* 34 (1992), 361-385.

Berger, M.A., Random affine iterated function systems: mixing and encoding, in *Diffusion Processes and Related Problems in Analysis, Vol. II: Stochastic Flows,* M. Pinsky and V. Wihstutz, eds., Birkhauser, Boston, 1992.

Berger, M.A. and Wang, Y., Bounded semi-groups of matrices, *Lin. Alg. Appl.* 166 (1992), 21-27.

Berger, M.A. and Wang, Y., Multi-dimensional two-scale dilation equations, in *Wavelets: A Tutorial in Theory and Applications,* C.K. Chui, ed., Academic Press, New York (1992), 295-323.

Books:

Berger, M.A., *Introduction to Probability and Stochastic Processes,* Springer-Verlag, New York, 1993.

Other Research Grants Awarded:

Probabilistic Methods for Image Generation and Encoding, National Science Foundation, Grant No. DMS-8915322, 1990-1992. Amount: $100,000.

Mathematical Sciences Computing Research Environments, National Science Foundation, Grant No. DMS-9105397, 1991-1994. Amount: $30,000.

Analysis of Dilation Equations, National Science Foundation, Grant No. DMS-9204514, 1992-1994. Amount: $45,000.

Automatic Target Recognition and Tracking, sub-contract from Clark-Atlanta University, ARPA, 1993-1995. Amount: $120,000.